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16. ABSTRACT

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It is pointed out that drainage should be thought of in developing the overall cross-sections of pavement. The paper discusses overall design in relation to trench sections and full-width drainage.

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STRUCTURAL SECTION DRAINAGE

W. R. Lovering* and Harry R. Cedergren**

SYNOPSIS

Water that cannot freely drain out of pavement bases is always a serious threat to the integrity of pavements. Excess water and poor drainage almost always lead to pavement failure.(1) (2)

The continued serviceability of any pavement depends upon prevention of the accumulation of excess water at all levels within the structural section and in the underlying basement soil. Standard practice should provide balanced designs in relation to the porosity or permeability of the "roof" of the structural section (the wearing course), the permeability and seepage potential of the "basement" soil beneath the structural section and the capabilities of the section for removing water. In this paper some methods are presented that make possible the development of reasonably balanced designs with drainage layers "built-in" as an integral part of the section. The importance of having drainage layers with adequate permeability is given special emphasis to demonstrate the value of layered drainage systems incorporating a protective layer of filter material and a drainage layer of coarse crushed rock or lean open-graded asphalt mix. The ability of open-graded asphalt mixes to transmit water may be verified by observing the flow of water which occurs at the edges of open-graded wearing courses immediately after rains.

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INTRODUCTION

Structural section drainage, as used in this paper, refers specifically to the removal of surface and seepage water from the various elements of the structural section of the pavement.

The pavement structural section may be designed with sufficient strength to support traffic loads over wet or even saturated soil, providing a hydraulic head does not develop beneath the pavement. Accumulations of water in the base or subbase, however, may cause distress, regardless of the thickness of structural section used. Water trapped in any element of the pavement or base may, as a result of normal deflections under traffic loads, exert pressures that will cause cracking or disintegration of the pavement or pumping of plastic soil into the base. If the road is constructed on a grade, water in the base will percolate down grade and, if the base is sufficiently porous to accommodate the flow of water involved until a means of escape is eventually reached, the pavement may not be damaged. Without adequate drainage design, variations in the permeability of the base, however, may cause a build up of hydrostatic pressure sufficient to lift the pavement from the base and lead to cracking or complete destruction of the pavement. If the design does not allow the lateral escape of the water, uplift pressures will develop at sag verticals.

Although many types of drainage installations may be used to fit individual conditions, this paper will be concerned with a type of installation which may be described as "built-in" or "integrated." In this type of design, complete layers of pervious materials are placed at the correct levels beneath the pavement surface to collect and remove seepage water entering the structural section, either through the pavement or from the underlying soil. The thickness and permeability of the drainage layers must be adequate to accommodate the seepage water that may develop.

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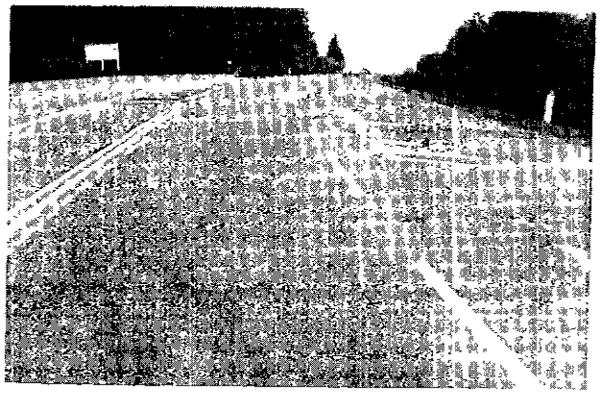
The layers of granular materials used for drainage will add to the structural strength of the pavement and the design of a drainage system of this type will be an integral part of the structural section design.



With insufficient drainage, water may flood base and rise through pavement.

To aid in evaluating the problem of designing drainage layers, hydraulic calculations were made of the discharge of water through these layers after entry into the structural section, both through the pavement and from the subgrade. These studies suggest that current design practices permit extreme unbalance of structural sections in relation to drainage. It is shown that pavements should be much more impervious than generally has been recognized, and that some commonly accepted drainage standards provide designs that cannot begin to cope with the amount of water that can enter the structural section.

Porous wearing courses allow both pavement and base to become flooded in a relatively short time, unless adequate drainage is provided. Unfavorable ground water conditions can do the same. This paper demonstrates that it is possible, often at no increase in cost and sometimes at a savings, to design structural sections with liberal capacities for the removal of seepage water.

If the greatest economy is to be effected, the design of the structural section and drainage must be adjusted to: 1) the permeability and cost of available materials, 2) the thickness of structural components required to provide the necessary strength, 3) the effective permeability of the basement soil, 4) the permeability of the wearing course, 5) the transverse and longitudinal grades involved, and 6) the distance the water must be transported to be removed from the structural section.

THEORETICAL CONSIDERATIONS

A Need for Realistic Drain Design Criteria:

Pavement engineers have been in accord, from the time of the earliest highways, that good drainage is vital to the continued life of any pavement that is exposed to the elements. Yet, even today, there is a surprising lack of respect for the basic laws of nature that determine the rate of flow of water through granular drainage systems.

Until fairly recent years, drains installed to remove water from beneath pavements were constructed of coarse open-graded rock which had a very high capacity when placed, but a few have learned by painful experience that this high capacity is not always maintained over a period of years. In many cases the fine silt sizes of the soil adjacent to the drains are carried into the void spaces of the drain rock by percolating water and the drains become completely clogged. This problem was recognized in dam construction and excellent criteria suggested by K. Terzaghi(3) have been used for years with great success for the design of drainage systems for dams and levees. These same criteria were used as a basis of a comprehensive study of drainage requirements made by the Corps of Engineers(4) in developing criteria for selecting a suitable grading for the drain rock or filter material for pavement usage. Further study by Roy L. Greenman(5) and others(6),(7) substantiated these requirements.

The criteria developed as noted above provide a means by which the grading of the drain rock or filter material may be adjusted to prevent intrusion and clogging by an individual soil that needs to be drained. There has been a tendency, however, to establish standard gradings for these materials and use them in standard drain designs without regard to the permeability of the material to be drained or the quantity of water to be accommodated.

Many of these standard filter material gradings have coefficients of permeability of only about 10 feet per day. Furthermore, the gradings are so critical that a variation of only one percent in the passing #200 size may reduce this permeability by fifty percent or more. There can be no doubt that filter material gradings must be designed to prevent clogging by the adjacent soil but it is equally essential that sufficient permeability be provided to permit the flow of water through the drain. Some typical gradings and corresponding rates of permeability are shown in Figure 1.

gates generally are considered unsuited to pavement base and subbase construction because they will not compact to form a firm working table for subsequent layers of the structural section unless high quality crushed rock is available. However, natural gravels, screened to a single size, may be obtained at reasonable cost in most areas, and may be used satisfactorily if cemented together with a

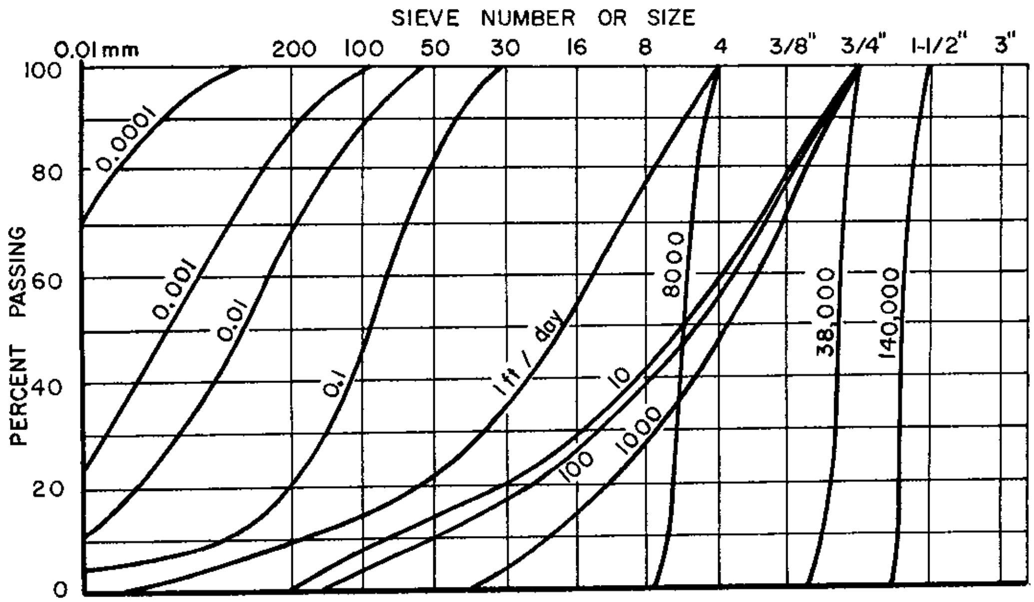


FIG. 1 SOME TYPICAL GRADATION CURVES AND PERMEABILITIES IN FEET PER DAY

With some soils, notably water-bearing silt or fine sand, it is doubtful if a single grading can be designed that will prevent clogging and yet provide the required porosity when placed on the flat grades normally used in highway construction. In many cases, it is best to resort to two-layer systems,(8) with a relatively fine filter layer against the soil to prevent silting and a second highly pervious open-graded layer for the removal of the water. The salient features of two-layer drains are compared with past and current drainage practice in Table I. (Next page).

Although it is possible to design systems of this type to provide very high capacity and multiple-layered systems with as many as 5 or 6 different gradations are in use in dams, the use of more than one drainage layer has been opposed in highway work because of the construction difficulties involved. One-sized aggre-

binder that will facilitate compaction without impairing permeability.

Lean asphalt mixes of coarse one-sized material, using an asphalt content of 2% to 3%, will compact readily to form a firm non-shifting foundation and yet will provide a high degree of permeability. The cost per ton of this mix will be higher than the cost of untreated aggregate but the overall cost per square yard of pavement may be less because of the reduction in thickness of the layer that will be possible because of the greatly increased permeability.

The drainage capacity of several open-graded mixes was verified by constant head permeability tests as shown by the coefficients of permeability in Table II.

TABLE I

PICTORIAL DEVELOPMENT
OF DRAIN DESIGN
FOR PAVEMENTS

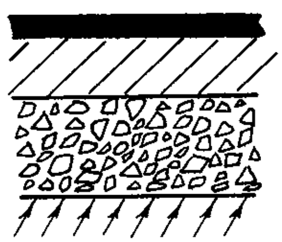
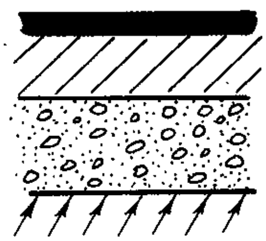
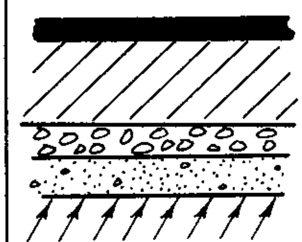
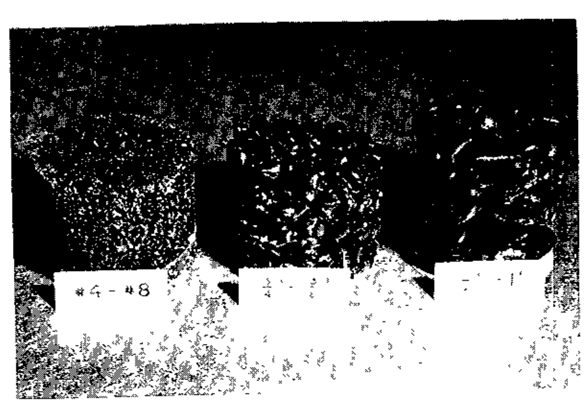
PERIOD →	Before 1940±	After 1940±	Proposed
POPULAR DRAINAGE DESIGN →	OPEN-GRADED ROCK (French Drains & Macadam Bases)	FINE-GRADED FILTER AGG. (Enough Fines to prevent intrusion of adjacent soil)	TWO-LAYER SYSTEMS (Built-in drains proposed in this paper)
TYPICAL X-Sec. →	 Seepage	 Seepage	 Seepage
RESISTANCE TO CLOGGING →	Poor May become completely clogged.	Excellent, when correctly graded.	Excellent, when provided with necessary filters.
DRAINAGE CAPACITY WHEN NEW →	Usually Excellent	Limited	Excellent - may be adapted to permeability of soil or pavement.
DRAINAGE CAPACITY AFTER SERVICE →	May be poor due to clogging.	No change.	Excellent - when properly protected.

TABLE II

Permeabilities of Untreated and Asphalt Treated Open Grade Aggregates

Aggregate Size	Permeability, ft./day Untreated	Permeability, ft./day Bound With 2% Asphalt
1-1/2" - 1"	140,000	120,000
3/4" - 3/8"	38,000	35,000
#4 - #8	8,000	6,000

The mixes used for these determinations are shown below.



The $1\frac{1}{2}''$ - 1" aggregate was well rounded with about 10% crushed particles, the 3/4" - 3/8" aggregate was about 50% rounded and 50% crushed, and the No. 4 to No. 8 was nearly 100% crushed. These tests indicate that open graded lean mixes of the type tested can be counted on to have at least 75 or 80 percent of the permeability of the raw aggregate. These test data were used in developing designs discussed in a subsequent part of this paper.

Infiltration of Surface Water:

Water that enters the structural section from beneath has been widely considered the cause of most serious drainage problems. In reality, this is only part of the problem of designing balanced structural sections. There is evidence that the amount of water seeping downward through pavements may actually exceed the quantity which may enter from the basement soil. Values of permeability reported by E. Zube(9) based on a test developed by the California Division of Highways, are certainly high enough to indicate the need for consideration of this factor in designing pavement drainage.

The test cited above is made by measuring the amount of water in milliliters that will be absorbed in one minute by an area of the pavement six inches in diameter. To promote wetting, a detergent is used in the water. Values measured range up to 600 ml. per minute when tests are made immediately after compaction of the pavement. Although a few months of summer traffic may reduce the permeability to values as low as 15, the data reported shows that the area between the wheel tracks and in the passing lane may retain a high degree of permeability and that this permeability may, if free escape is provided beneath the pavement permit infiltration exceeding the amount of normal rainfall. Bituminous concrete permeabilities reported by Barber and Sawyer(10) for compacted laboratory specimens also permit infiltration exceeding normal rainfall.

The permeability of the pavement may be reduced by proper mix design and adequate compaction but unless a completely water-tight pavement is assured, provision must be made for removing any water that percolates into the base. The quantity of water that must be removed will depend on the porosity of the individual pavement and the rainfall rate that may occur in that particular area. Calculations shown in this paper are based on inches of rainfall which would penetrate the pavement and for design purposes would be equivalent to some percentage of the actual rainfall. The actual quantity used in the drainage design would then be determined by the porosity of the pavement and the rainfall rates to be expected in the particular area. A few simple calculations based on principles of laminar flow of water through porous media throw considerable light on the problem and, furthermore, reveal the complete inadequacy of the low permeability filter materials.

Figures 2 and 3 have been prepared to illustrate the thickness of various pervious materials needed to accommodate possible infiltration rates. These charts show the discharge (water removing) capacity of pervious layers of various thicknesses and permeabilities in relation to the quantity of water infiltrating through the pavement surface. Figure 2 represents pavements constructed on a 2% cross slope and Figure 3 pavements on a 5% longitudinal slope. The water removing capacities of several drainage layers are shown as horizontal dashed lines. The cumulative infiltration quantities for several rates of infiltration are shown as solid diagonal lines. These lines are straight because of the log-log plotting of the data. The cumulative quantities are the amount that would enter a one-foot wide slice of pavement at the stated rates. The cumulative quantities are shown in cubic feet per day, whereas the infiltration rates are shown in ml. per minute through a 6" dia. area and in inches of rainfall per day. A rainfall of 2 inches a day is about equal to a steady rate of one ml. per minute on a 6-inch diameter area. The two figures show that pavements that are considered adequately tight can permit comparatively large rates of infiltration, and that drainage layers of "normal" permeabilities cannot begin to remove quantities that can enter through porous pavement surfaces. For example, as shown on Fig. 2, a 36" layer of material on a 2% grade with a permeability of 10 feet a day is required to drain the water that enters a 15-foot length of pavement at a rate equivalent to 1/2 inch of rainfall per day. In contrast, only 3 inches of material with a permeability of 10,000 feet per day can remove the water that enters a 1000 foot length of pavement at the same rate.

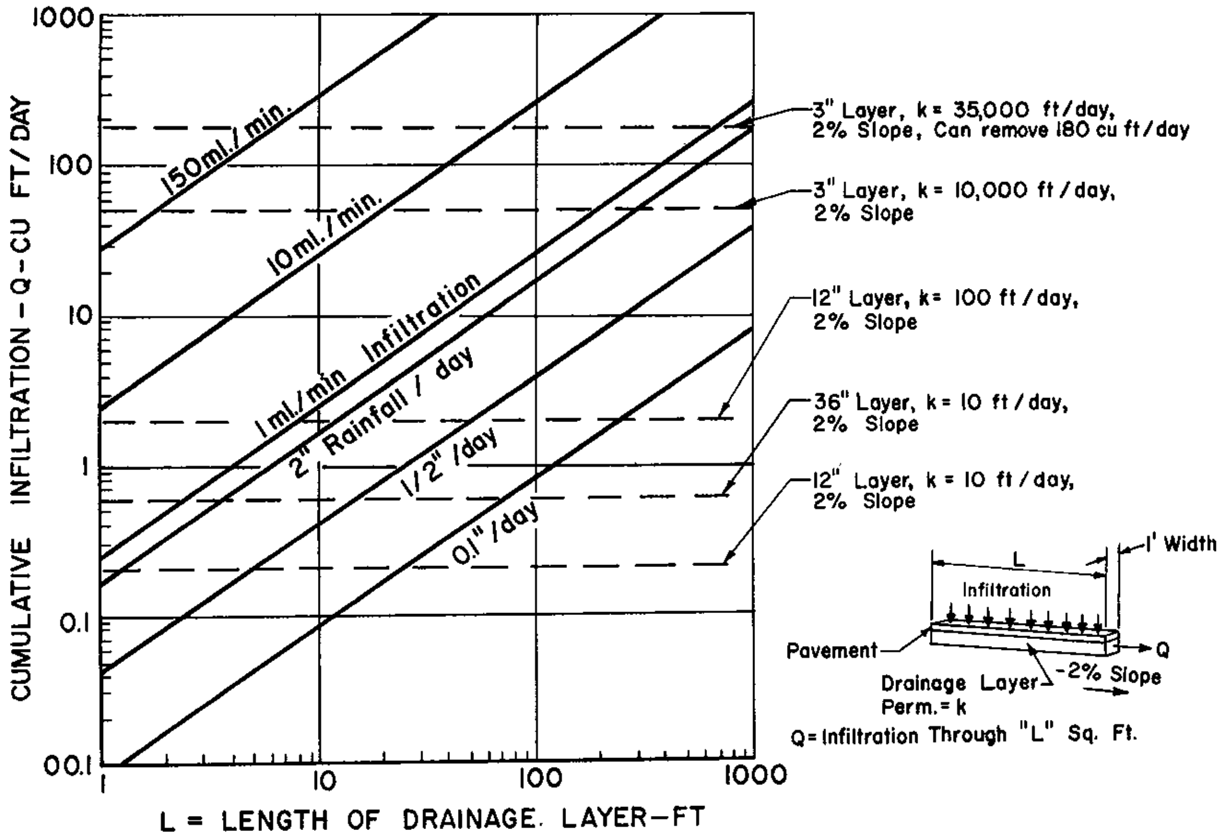


FIG. 2 DISCHARGE CAPACITIES OF DRAINAGE LAYERS ON 2% SLOPE VERSUS CUMULATIVE INFILTRATION QUANTITIES

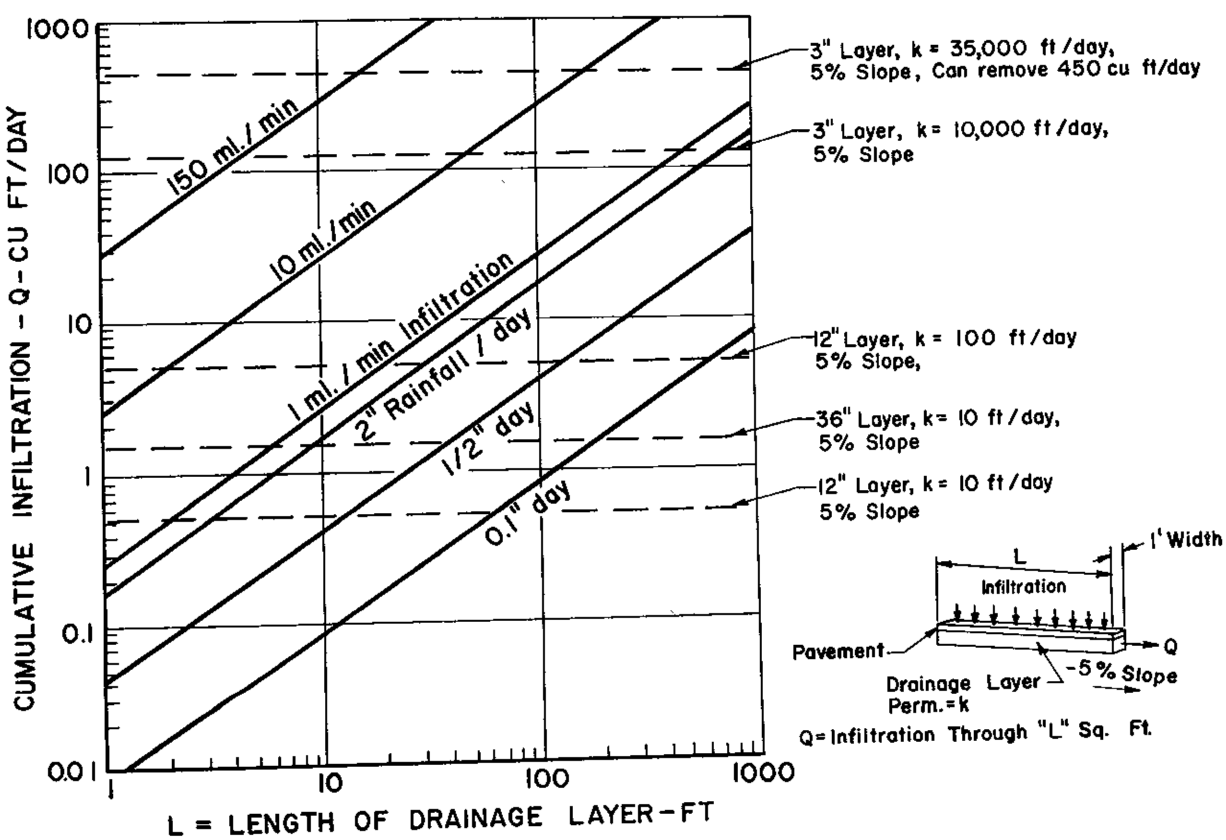


FIG. 3 DISCHARGE CAPACITIES OF DRAINAGE LAYERS ON 5% SLOPE VERSUS CUMULATIVE INFILTRATION

These figures point up the importance of using dense graded mixes for wearing courses, and of constructing bituminous pavements early enough in the season to allow traffic to tighten the surface before much rain falls on the pavement. Even with these precautions, new pavements seldom have infiltration rates less than 10 or 15 ml. per minute. Balanced design can be obtained for high infiltration rates, however, by using two mixes for the asphalt concrete pavement. The upper lifts should be a dense mix capable of forming a reasonably water-tight roof and the lower lift, or asphalt concrete base, should be a very open-graded mix connecting to drains for the removal of water. The City of Oakland, California, has successfully used a similar design for the construction of reservoir linings where any uncollected leakage is a hazard to adjoining property. An open-graded asphalt mix was used for a drainage layer beneath a covering of prefabricated asphalt panels.

Open-graded base layers must be provided with drainage outlets to avoid creation of reservoirs that will retain water and cause damage to pavements. Means for draining pervious base layers are an essential part of their design and should be adapted to individual conditions. Drainage of the open graded base may be achieved by full-width construction of this layer or by means of transverse or longitudinal drains. If transverse drains are used, the interval of spacing will be determined by the drainage capacity of the open-graded layer. This capacity will depend on the permeability and thickness of the open-graded layer and the grade of the highway as illustrated in Figs. 2 and 3. On flat grades full width construction or longitudinal drains may be necessary, but where the grade permits, transverse drains as illustrated in Fig. 4 generally will prove more economical.

Removal of Ground Water:

Many drainage troubles and deteriorated pavements can be attributed to water that enters the structural section from below. Ground water is most troublesome in areas where the road grade is near or beneath the surrounding ground water level; for example, in sections of freeway that are depressed below the surrounding ground and in mountainous areas where the road is deep in wet cuts.

In the past there has been no simple procedure for designing drainage installations for removing groundwater seepage but a method has been developed recently[11] embodying the use of flow nets. Using the flow-net method, the curves in Figure 5 were obtained for a road section that is subjected to rising ground water. A half-width of 29 feet was assumed with a transverse slope of 2%, and an upward seepage gradient of 0.4 in the basement soil. A shallow longitudinal collector drain was assumed beneath the outer shoulder. For steady seepage under these conditions, the curves in Figure 5 give the relation between soil permeability and the thickness and permeability of drainage layers required to remove the incoming seepage.

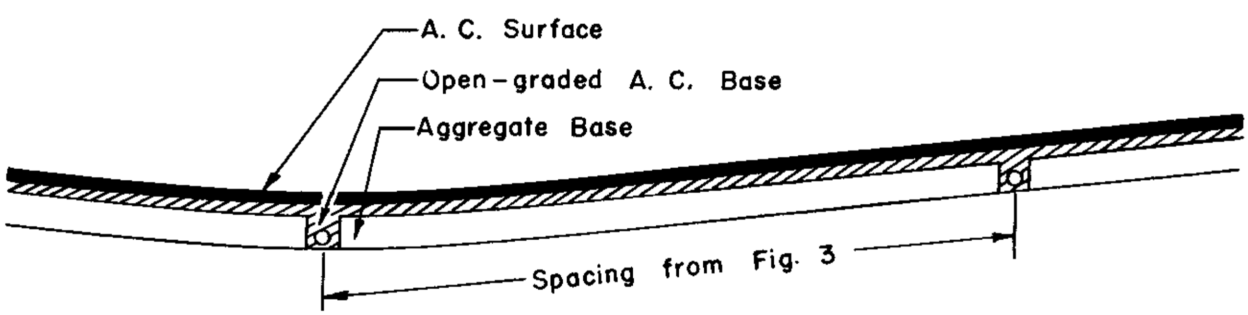


FIG. 4 PROFILE SHOWING CROSS DRAINS FOR REMOVAL OF WATER FROM OPEN-GRADED PAVEMENT BASE.

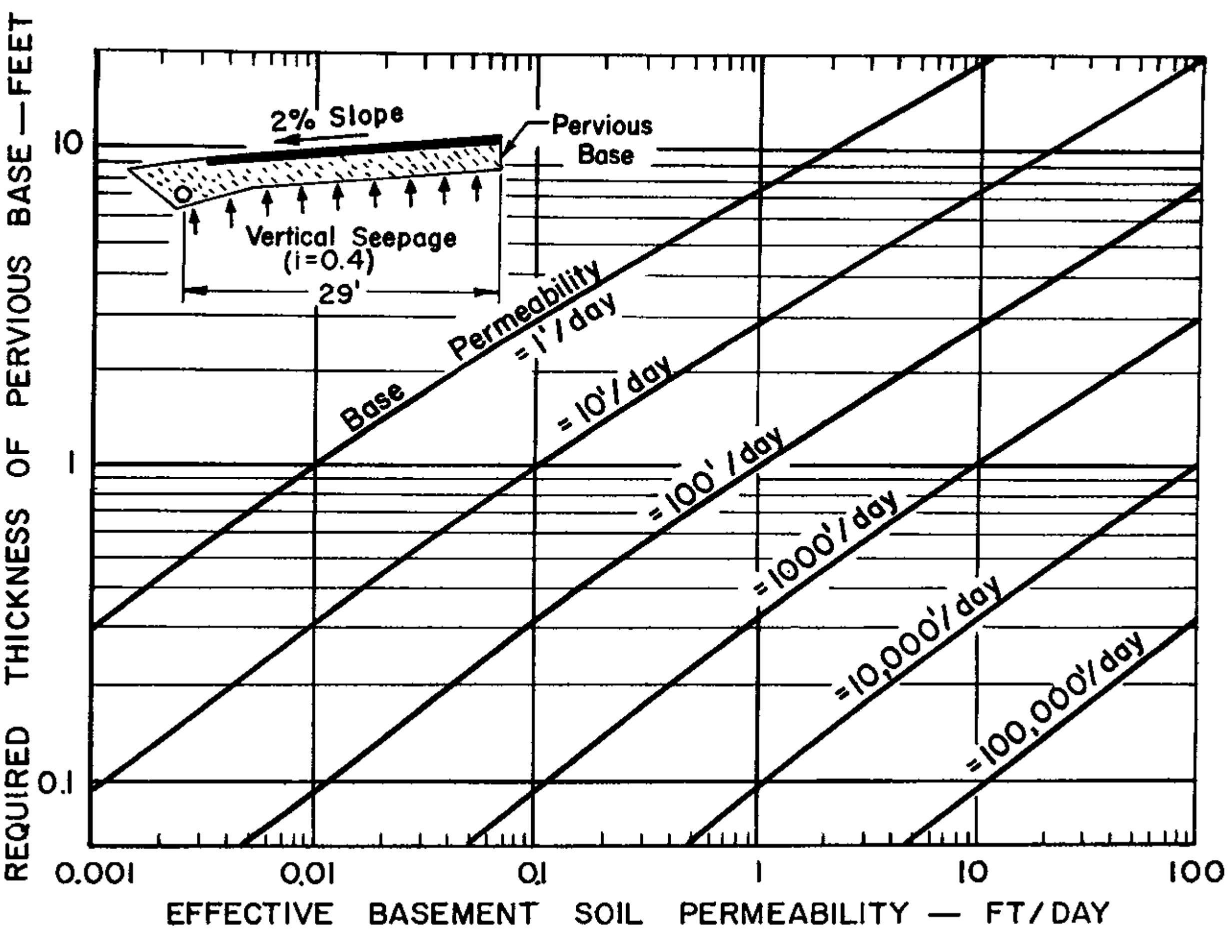


FIG. 5 RELATIONSHIP BETWEEN THICKNESS OF BASE AND PERMEABILITY OF SOIL AND BASE

For the conditions represented in Figure 5, a three-foot thickness of filter aggregate with a permeability of 10 feet a day, provides protection against seepage from soils having permeabilities up to one foot a day (7×10^{-4} ft/min). One foot of filter aggregate with a permeability coefficient of 1000 feet a day protects against seepage from soils having permeabilities up to 10 feet a day, and about 0.3 feet of open-graded aggregate with a permeability of 100,000 feet a day protects against seepage from soils having permeabilities up to 100 feet a day (0.07 ft/min). The drainage potential of open-graded aggregates which may be used in two-layer systems is believed self-evident. The economic advantage of two-layer drainage systems incorporating open-graded lean asphaltic mixes, or untreated aggregates of high permeabilities, are discussed in another part of this paper.

The above examples were presented to show some of the wide variations in drainage that can be encountered in pavement design, and to emphasize the need for a rational analysis of drainage requirements. The drainage systems described in this paper as "built-in" drainage layers, can be "tailored" to the needs of the job, and can provide reasonable margins of safety with respect to quantities of water that must be removed. Prevention of silting and clogging of these systems by properly placed filter layers is paramount to their success, and a vital element of their design and construction. Some of the practical considerations that enter into drainage design are discussed in the following paragraphs:

PRACTICAL DESIGN CONSIDERATIONS

Special Requirements for Structural Section Through Seepage Areas:

In seepage areas, the moisture content of the soil will be high and, unless seepage is strictly seasonal, it will not be possible to dry the soil to optimum moisture during the construction period. Under these conditions, lower soil densities in the subgrade will be obtained and the support provided by the soil will be less than that indicated by the standard test procedures. Because of the lower density and poor support provided by the soil, it is usually necessary to increase the structural section thickness through seepage areas. This is normally accomplished by an increased thickness of granular base in the lower part of the structural section. During construction of the pavement, the wet soil will not provide adequate support for the construction equipment and it will be necessary to place the first increments of granular base in thicker lifts to prevent shearing and displacement of the underlying soil by construction equipment. The use of these thicker lifts may result in substandard density of the base material and this factor should be considered in the design of the upper elements of the structural section.

Design procedures for establishing the thickness of structural section vary somewhat in the assumed soil moisture which will exist during the life of the pavement. Some methods assume that the soil will be completely saturated while others, particularly those used in drier areas, assume only a partial saturation. In areas where seepage water is likely to occur, the structural section should be designed for complete saturation of the soil, unless the soil is of a free-draining type and the water table can be lowered by installation of underdrains.

Requirements for Drainage:

Drainage systems must be adapted to the needs of the job. For example, drainage systems may be designed either to prevent water from entering the base course or soil subgrade, or to remove water which has entered before it can damage the pavement. The choice often is one of selecting the most economical <u>that will do the job properly</u>.

An example of the first type would be the use of deep longitudinal drains to lower the water table through an area of high ground water. Deep longitudinal underdrains of this type may be effective in homogenous soils or in stratified materials, if the bedding planes have not been distorted. In areas where geologic folding or severe land mass movement has occurred, however, it may not be practical to intercept the subsurface seepage in this manner.

In areas where interception of seepage is not feasible, the only effective means of control is through use of a blanket or layer of drain rock or filter material under the full width of the structural section. This drain layer must discharge either into collector drains or open side ditches.

If the basement soil is sufficiently fine, with correspondingly low coefficients of permeability, a layer of filter material alone may provide all the capacity required without the thickness being excessive. If the material to be drained consists of water bearing gravel, a very open drain rock will be needed to prevent the build up of hydraulic head beneath the pavement. Water bearing soils with gradings intermediate between these two extremes may require two-layer systems, with an open drain rock used to obtain the needed capacity and an appropriate layer of finer filter material used to prevent clogging of the drain.

The success of any sub-drainage system depends upon satisfying the following two basic requirements:

1. It must have sufficient capacity to quickly remove free water from beneath the pavement.
2. It must retain this capacity throughout the design life of the pavement.

Full Width Construction:

Lateral drainage may be provided by full width construction in which the layers of base and subbase are carried completely across the width of the roadbed. To be effective, the base material must be sufficiently pervious, and free access to side ditches must be assured. The necessity of special requirements for seepage areas must not be overlooked, however.

Normal base or subbase material will accommodate only a minor amount of seepage. In areas where subsurface seepage is expected, an analysis should be made to estimate the quantity of flow that will occur and special drainage layers designed that are capable of removing this water. The design developed should be based on the permeability of materials available and the thickness required for structural strength with the actual design used determined by the cost of the several possible alternates. In full width construction the pervious material used provides for lateral flow into side ditches. The side ditches take the place of longitudinal perforated or porous pipes that would be placed in a trench section.

When full-width construction is depended upon for drainage, it is important that proper maintenance practices be employed. Improper maintenance procedures, such as blading soil from the ditch against the granular material, may prevent escape of the water from the pervious drain material into the side ditch and completely destroy the effectiveness of the drainage layer.

Another factor which must be considered is the added cost of the base or drain material necessary in the shoulder areas and the additional excavation in cuts required for the side ditches. These costs must be balanced against the cost of drain pipes which would be used in a trench section.

Trench Sections:

Trench sections, that is, structural sections in which the base is set down into the basement soil, have been criticised for many years and the poor performance of miles of pavement with this type of design justifies this criticism. There is no reason, however, why trench sections may not be entirely satisfactory, if properly designed and constructed.

The requirements of a satisfactory design are 1) adequate structural section thickness to support traffic loads over a saturated foundation soil, 2) protection of the base or other elements of the structural section from infiltration of surface water by an impervious pavement free of cracks, and 3) provision of a positive subsurface drainage system, when required, with capacity sufficient to remove all seepage water quickly without the development of hydrostatic head.

With the R-value method of design[12] it is assumed that the soil will become saturated and test values used for determining the required structural section thickness are based on this condition. With this method, saturation of the soil should not be detrimental if hydrostatic head does not develop beneath the pavement and if the basement soil is sufficiently pervious to avoid the possibility of pumping under the action of traffic. A trench section may, however, result in lack of edge support which could cause failures along the edges of the pavement. This could occur if the weight of base and surfacing in the shoulder area is not sufficient to resist the forces developed through plastic flow of the basement soil. This may not be as serious a problem on four-lane construction, as traffic normally will not drive close to the pavement edge and the base thickness ordinarily used to meet the demands of the shoulder traffic will be sufficient to prevent edge failures.

Considering the factors discussed above, it appears that a trench section may be entirely satisfactory, with the possible exception of reduced edge support, if effective drainage is provided. A major advantage of a trench section is a greatly reduced construction cost, particularly if heavy grading is involved. If a trench section is constructed, however, the following must be provided:

1. A pavement sufficiently impervious to prevent excessive amounts of water from percolating into the base course.
2. A design that will not develop cracks and permit water to percolate freely into the base.
3. A positive subsurface drainage system for wet cuts so that any subsurface water developed may be collected quickly and removed from the pavement section.
4. A positive cut-off or interceptor trench at the lower ends of cuts to prevent water from the cuts percolating down grade through the pavement base.

In pavement construction of the last few years, it does not appear that any of the above requirements have been fulfilled consistently.

One specific weakness has been the failure to construct subsurface drainage systems that will quickly remove water that collects in base courses or in pervious blankets provided for drainage. The inadequacy of these drains has been caused primarily by attempting to combine a filter material and a drain material into one product. A material fine enough to act as a filter often has insufficient capacity as a drain when compacted to the degree necessary under a pavement. Attempts to provide the needed capacity with this type of material results in an excessive thickness, increasing the cost of imported material and the amount of excavation required in cuts.

Two-layer systems, consisting of a blanket or layer of fine filter material adjacent to the soil and a layer of very open drain material above the filter, can, as shown in the preceding pages, provide large drainage capacity. This type of system may materially reduce the cost of drain installations because of possible reductions in the overall thickness of the drainage layers. A typical application is shown in Fig. 6.

would provide all the drainage necessary for most waterbearing soils with ample allowance for partial clogging on the upper and lower boundaries. The construction of such a layer, together with, say, a 4" thickness of underlying filter material, should cost less than the thick layers of filter material now being used, when thick sections are not required for structural support. The asphalt content need be no greater than required to provide the necessary cohesion. Stripping of the asphalt films which may occur in a lean mix, if it occurred, would take place after construction is completed and is of no concern as it would in no way impair the effectiveness of the drain layer.

Cost Comparisons:

Let us consider alternate subsurface drainage installations, one using a standard filter material and the other a two-layer system, using a lean open-graded asphalt concrete mix with a thin layer of filter material protecting the open layer from clogging.

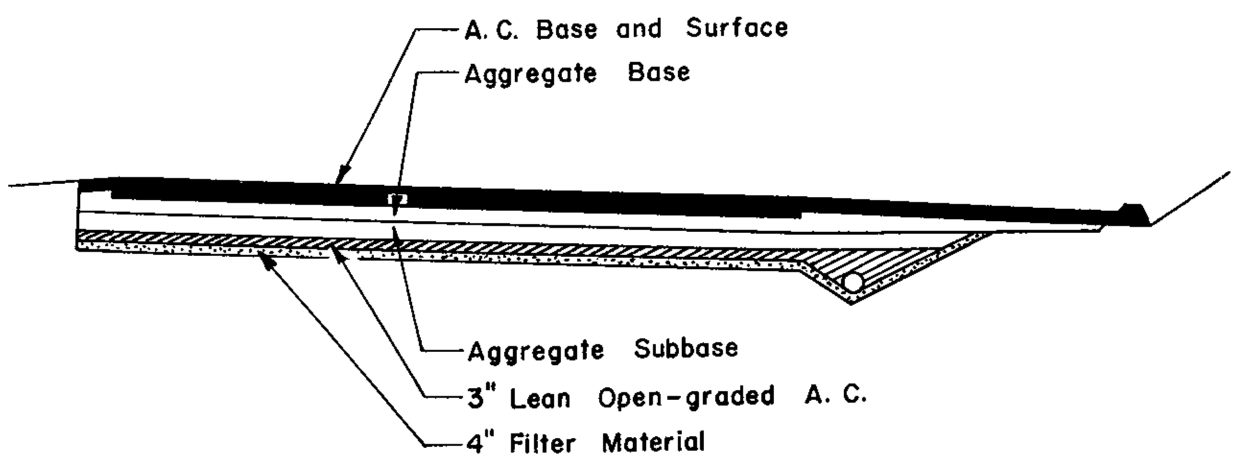


FIG. 6 CROSS-SECTION SHOWING TWO-LAYER DRAINAGE SYSTEM.

It is recognized that the coarse one-size material required for high permeability often will present construction difficulties during the placement of the superimposed layers. These difficulties may be avoided, however, by mixing the open-graded aggregate with 2% to 3% of asphalt so that it may be compacted to provide a firm support for construction of the overlying pavement section. A 4" thick layer of asphalt treated material of, say, 1½" to 1" rock,

For this design, let us assume the following:

Permeability of waterbearing soil	1 ft/day
Permeability of filter material	10 ft/day
Permeability of 3/4-1/2" lean open graded AC	35,000 ft/day

Using the boundary conditions represented in Figure 5, the thickness of each material required may be taken from this figure or by using flow-nets in the manner described in a recent paper.(11) For the conditions cited, the required thickness of filter material alone would be 3.0'. For the open-graded asphalt concrete mix the thickness required would be approximately 0.1'. A filter layer of, say, 4" to 6" will be required beneath the open layer to prevent clogging and the lean asphalt concrete mix must have a practical minimum construction thickness of, say, 3".

The cost per square yard of each installation may be estimated if a reasonable cost figure is assumed for each of the materials required. The cost per ton of filter material may be obtained from typical current bid prices. A reasonable cost per ton for the open-graded mix may be obtained from typical current bid prices for asphalt concrete pavement by adjusting for the lower asphalt content required and then adding an allowance (say $1.00 per ton) to compensate for the fact that one size aggregate is required. The following prices should be sufficiently comparative to use for illustration:

Filter Material	$5.00 per ton
Open-graded AC mix (Plant mixed)	$7.50 per ton

Based on these prices, the cost per square yard of the alternate designs cited above would be as follows:

Filter material alone (k = 10-ft/day):

$$3.0 \text{ ft} \times 9 \text{ ft}^2 \times \frac{135 \text{ lbs}}{\text{Ft.}^3} \times \frac{\$5.00}{2000 \text{ lbs}} = \$9.10/\text{sq.yd.}$$

Combined filter material and open-graded AC (k = 35,000 ft/day for AC):

$$0.33 \text{ ft} \times 9 \text{ ft}^2 \times \frac{135 \text{ lbs}}{\text{Ft.}^3} \times \frac{\$5.00}{2000 \text{ lbs}} = \$1.00/\text{sq.yd.}$$

$$0.25 \text{ ft} \times 9 \text{ ft}^2 \times \frac{125 \text{ lbs}}{\text{Ft.}^3} \times \frac{\$7.50}{2000 \text{ lbs}} = \$1.06/\text{sq.yd.}$$

TOTAL $2.06/sq.yd.

The above example is admittedly a comparatively extreme case with a coefficient of permeability for the soil which would be expected from moderately pervious soils, such as waterbearing silty gravels. Although conditions as bad as this will be encountered frequently in some areas and worse conditions will sometimes be encountered, it may be well to consider the relative cost for conditions involving a less permeable soil. The following should be typical of a waterbearing silt:

Permeability of Soil	0.1 ft/day
Permeability of filter material	10 ft/day
Permeability of lean open-graded AC	35,000 ft/day

The thickness of each material required, obtained in the same manner as above, would be:

Filter material alone	1.0'
Open-graded lean AC	0.1'

An adequate design using the open-graded AC mix with an allowance for some clogging of the AC mix along the boundaries between AC mix and untreated aggregate would be:

.33' filter material

.25' open-graded lean AC mix

The comparative cost per square yard of the above installations would be:

Filter material alone:

$$1.0 \text{ ft} \times 9 \text{ ft}^2 \times \frac{135 \text{ lbs}}{\text{Ft.}^3} \times \frac{\$5.00}{2000 \text{ lbs}} = \$3.03/\text{sq.yd.}$$

Combined filter material and open-graded AC:

$$0.33 \text{ ft} \times 9 \text{ ft}^2 \times \frac{135 \text{ lbs}}{\text{Ft.}^3} \times \frac{\$5.00}{2000 \text{ lbs}} = \$1.00/\text{sq.yd.}$$

$$0.35 \text{ ft} \times 9 \text{ ft}^2 \times \frac{125 \text{ lbs}}{\text{Ft.}^3} \times \frac{\$7.50}{2000 \text{ lbs}} = \$1.06/\text{sq.yd.}$$

TOTAL $2.06/sq.yd.

From the above examples, it is clear that for the more severe drainage situations the open-graded asphalt concrete mix could be constructed at less cost than the design using filter material alone. This is the case in spite of the fact that a much greater capacity has been provided with the open-graded asphalt concrete drainage layer.

In these examples it has been assumed that the source of water is the underlying soil and the drain is placed beneath the structural section. If water is entering through the pavement, a drain may be required above the aggregate base and subbase. The design of this drainage layer can be developed from charts such as those in Figure 2 and Figure 3, as explained previously. Similar charts can readily be developed for other slopes and dimensions.

With a positive drain in locations subject to water infiltration, it should be perfectly feasible to construct a trench section to give entirely satisfactory service. This would eliminate the cost of excessive thicknesses of base or pervious material in the shoulder area and avoid the extra width necessary in cuts to accommodate side ditches. It would also, if cut-off trenches are provided at the ends of cuts, prevent seepage water from draining over the fill which frequently causes slumping of fill slopes with attendant cracking of the pavement.

Relation to Structural Section Design:

The foregoing illustrates the savings in cost that may be effected by the use of thin layers of very open highly permeable lean asphalt mixes for drainage. A practical approach to the design of the entire structural section, however, requires a balancing of the requirements for structural section strength with those of drainage. There would be no advantage in using a more expensive material in a thin lift if an appreciable thickness of aggregate base is required for structural strength and a less expensive material with adequate permeability is available.

For example, for the conditions shown in Fig. 5, a basement soil of clayey silt on a 2% slope having a coefficient of permeability of 0.01 feet per day would require only 0.32' of filter material with a permeability of 10 feet per day. This same soil would require from 0.8' to 1.3' of aggregate base beneath the pavement if the soil is properly compacted and could require as much as 2' of aggregate base if rising ground water prevents proper compaction of the soil. In this case, the use of a 10 feet per day permeability filter material for the entire drainage layer would be the more economical choice since the drainage layer would serve as part of the structural section.

The low permeability filter materials must be used with caution, however, because minor variations in the grading may drastically reduce the permeability. Usually, it will be necessary to wash the aggregate to assure maintenance of the low dust content required for a permeability of ten feet per day in a graded aggregate, and with some materials degradation caused by handling and placing may increase the dust content sufficiently to impair the permeability.

SUMMARY

Through a desire to avoid troubles that are caused by infiltration and clogging, the pendulum of drainage design has swung to the extreme of producing structural sections that do not always have adequate factors of safety for water removal. As a consequence, when appreciable quantities of water must be removed, drainage systems frequently are overloaded and the pavements are not adequately protected. Failures are the result. Although it is never possible to predict with exactitude the amounts of water that will enter new pavements, methods of analysis are available that permit reasonable estimates for known degrees of permeability of pavement and basement soil. Computations by these methods show a need for providing designs that are capable of removing more water than is possible with conventional designs. It is shown in this paper that it is possible to provide - usually at no increase in cost, and sometimes at considerable savings - drainage systems with highly increased water-removing capacities. The paper presents designs utilizing very open-graded filter layers, stabilized with small amounts of asphalt when necessary, and protected with transition filters when necessary. These designs may be thought of as "built-in" or "integrated" drainage systems. They are part of the structural section, and help carry traffic loads. They can be "tailored" to meet prescribed degrees of permeability of both pavement and subgrade; hence, their use results in a structural section design that assures a reasonable balance with respect to ability to remove water. The provision of adequate drainage capacity eliminates the primary objection to trench section design and makes possible the economies of this

type of construction.

The importance of "designing" the drainage system cannot be over-emphasized. Both structural section requirements and geometric design must be considered when designing the drainage system. To be economical the drainage system must utilize to best advantage materials readily available in the area and provide only the capacity necessary to assure removal of the water which may enter a particular pavement section. If failures are to be avoided, however, the system must have adequate capacity and must maintain this capacity for an indefinite period of time.

In designing the drainage system, the following must be considered:

1. Expected permeability of pavement surface and probable precipitation.

2. Permeability of the water bearing soil and probable hydraulic head.

3. Drainage gradients, both transverse and longitudinal, available for removal of water.

4. The permeability of the various elements of the drainage system.

5. Proper grading of drainage aggregate and transition filters to prevent clogging.

6. Provision of outlets as required for the capacity of the drainage layers.

It is usually not possible to predict with certainty, during the preliminary investigation, the exact extent or character of the formations that will be encountered in cuts. It should, therefore, be the responsibility of the construction engineer to reevaluate the drainage design after a study of the formations actually exposed by the grading operation and make any adjustments required. The procedures presented herein for designing drainage systems will provide reasonable factors of safety.

The drain outlets should be marked when constructed and should be routinely checked by maintenance forces, at least annually, to make sure they have not become clogged by vegetation or foreign objects. A complete and expensive system of drainage may become virtually inoperative by clogging of the last few inches of the outlet.

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